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Automatic Recognition of Solar Features for Developing Data Driven Prediction Models of Solar Activity and Space Weather

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14. ABSTRACT
Solar sequential chromospheric brightenings (SCBs) are point brightenings that are typically observed in conjunction with flares that have associated coronal mass ejections (CMEs). To characterize these ephemeral events, we developed automated procedures to identify and track loci of bright pixels of in two-ribbon solar flares and the SCBs using the ISOON telescope's H-alpha images. This software package extracts physical quantities such as temporal variation of flare and SCB intensities, apparent proper motion of the moving ribbons, and the speed of SCB intensity propagation (Kirk et al. Accepted). The extracted features can be overlaid onto complementary images to obtain Doppler velocity and magnetic intensity measurements. We present evidence that SCBs are a different class of brightening than the flare ribbons. We also put forward a simple model for observed SCB propagation speeds and hypothesize a physical origin.

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Introduction

Active regions on the Sun can produce a variety of distinct dynamic features including sunspots, flares, prominences and occasionally mass ejections. Solar active regions are a major source of space weather. Historically, these active regions have been identified and characterized manually. To better understand the dynamics of solar active regions and their associated phenomena, data from different sources must be utilized and several similar active regions must be analyzed. This necessitates an automated approach to correlate several seemingly disparate data sets. In the past, a few different automated methods have been developed to simultaneously analyze flare ribbons across multiple sources of data (Qu et al. 2003; Maurya & Ambastha 2010; Gill et al. 2010).

First observed in 2005, sequential chromospheric brightenings (SCBs) appear as a series of spatially separated points that brighten in sequence (Balasubramaniam et al. 2005). The sequential nature of the point brightening gives the appearance of a progressive traveling disturbance. SCBs are observed as both single and multiple trains of brightenings in association with a large-scale eruption in the chromosphere or corona. The loci of brightenings are seen in a time-series of full-disk Hα images as emerging predominantly along the axis of the flare ribbons. Physically, SCBs are closely correlated with solar flares, coronal restructuring of magnetic fields, halo CMEs, EIT waves, and chromospheric sympathetic flaring (Balasubramaniam et al. 2005). Pevtsov et al. (2007) show that these physical correlations are consistent with several properties of chromospheric evaporation.

Computational Codes

This report presents the results from a new automated method of identifying and tracking SCBs and associated flare ribbons described by Kirk et al. (Accepted). This tracking technique is different than previous flare tracking algorithms in that it identifies and tracks subsections of the flare from pre-flare through the impulsive brightening and the exponential decline. This allows measurement of the temporal variation in intensity, position, photospheric magnetic field, as well as Doppler intensity of each individual flare kernel. This tracking algorithm is also adapted to identify and track the temporal evolution of the ephemeral SCBs associated with the flaring region.

Examining individual flare kernels, several physical quantities can be extracted. First it is most apparent that a majority of the flare kernels do not track the flare ribbon for the entire duration of the flare. This is because an individual kernel may appear in the impulsive phase of the flare. Also, kernels may disappear. Most likely these kernels merged with another at which point their unique identity was lost. Others show the characteristic exponential dimming that is seen in the characteristic flare intensity curves. This suggests that the substructure within a flare ribbon has some impulsive brightening within the overall topology of the exponential decreasing intensity.

Individual flare kernels are not a good indication of overall flare behavior, however when taken in aggregate, flare kernels reproduce overall topology of the flare. Integrating each of these intensities over each time step yields a flare intensity curve that reproduces the curves. This implies that the flare kernels have enough spatial and temporal coverage to adequately characterize the flare ribbons they are tracking.

Procedures

The trajectories of flare kernels offer insight into the motions of the flare ribbons as they evolve through the erupting flare. The initial out flow of the two ribbons near the flare peak at 16:49 UT, but as the flare continues to evolve, there is a more motion along the flare ribbons as the overarching loops readjust after the reconnection event. The mean velocity remains below 0.5 km s^{-1} throughout the flare even though the total velocity changes significantly.

Integrating the unsigned speed for each image's kernels gives a different way to examine the evolution of the flare ribbons. In general, the same shape as the intensity curve is followed. In the May 6, 2005 event, the speed curve more closely follows the GOES x-ray intensity curve rather than the Hα curve. In the November 11, 2004 event, the limb geometry of the flare as well as the noise in the original dataset interferes with producing a clear curve. Even with these difficulties, a clear increase in total speed can be seen near the peak of the flare. A continuum integrated speed level of a couple km s^{-1} is consistent in each event indicating the quality of data and tracking software.

Plotting the integrated speed of displacement over an Hα gives context to the integrated speed curves. There is significant motion along the flare ribbons as well as the outflow away from flare center. Some of the flare kernels that showed the greatest speed did not also have the greatest displacement. This is due to impulsive brightening caused by short-lived compact masses of hot plasma moving along low-lying magnetic loops.

When the tracked flare kernels are overlaid on GONG line of sight magnetograms, a measurement of magnetic flux under the flare ribbons is taken. There is only a weak positive correlation between peak H-α intensity and integrated magnetic flux. As expected, the brighter the flare kernel the stronger the underlying magnetic field. Since GONG magnetograms are taken in the photosphere at a sixteenth the resolution of ISOON, it is not surprising that the relationship observed is weak.

Sequential chromospheric brightenings, although related to the erupting flare ribbons, are distinctly different than the flare kernels. Six SCBs are chosen from the May 13, 2005 event as an example of these ephemeral phenomena. The SCB intensity curve is significantly different than the flare kernel curves. SCB curves are impulsive with a sharp peak and then a return to background intensity in the span of about 12 minutes. Nearly all of the SCBs examined peak before the peak of the flare intensity curve. About ten percent of SCBs appear to have more internal structure than the other SCBs and last noticeably longer. This is most likely caused by several SCB events occurring in succession that are unable to be resolved.

If the Hα intensity of the entire population of SCBs are plotted versus time, it clearly shows a small time window when SCB occur. SCBs begin brightening about 30 minutes before flare peak and return to background intensity about 20 minutes after. In contrast, the flare intensity curve can remain above pre-flare levels for several hours. The relatively short duration of SCBs implies a distinctly different physical mechanism is causing the sequential brightening as opposed to the flare ribbon brightening.

The peak brightness of SCBs have a sharp exponential decline as a function of time. About 50 minutes after the peak SCB brightness, typical SCBs have intensities less than 20% above background intensity in the May 6 and 13, 2005 events. Statistics from the November 9, 2004 event are dominated by the noise of the data and do not produce interpretable data. SCBs tend to cluster together in time as well as distance with two larger groups dominating the plots. Fitting a slope by eye to these two groups yields two propagation speeds: a fast and slow group. The May 6th event has propagation speeds of □140 km s^{-1} and □47 km s^{-1}. The May 13th event has propagation speeds of □144 km s^{-1} and □44 km s^{-1}. Examining SCB peak intensity levels as a function of distance, again a sharp peak and an exponential decline is seen as SCBs propagate away from flare center.

A measurement of the magnetic flux underlying the SCBs is made when the positions of the tracked SCB is overlaid on GONG line of sight magnetograms. The integrated unsigned magnetic field does not show any noticeable correlation with the peak intensity, distance from flare center, or duration of SCB. Higher resolution magnetograms are needed to fully investigate the relationship between SCBs and photospheric magnetic intensity.

Examining Doppler velocity measurement from the SCB locations reveal three distinct types of SCBs. A type 1a SCB has an impulsive intensity profile as well as an impulsive negative Doppler profile both of which occur simultaneously or a few minutes either side the peak line center brightening. A type 1b SCB has a similar intensity and Doppler profile as a type 1a but the timing of the impulsive negative velocity occurs several minutes after the peak intensity of the SCB. The typical type 1b SCB has a negative velocity that peaks 10 minutes after the peak intensity. A type 2 SCB has a broad Hα intensity and positive Doppler profile. The timing of both is nearly coincidental. A type 3 SCB begins as a broad Hα intensity and negative Doppler profile much like a type 2. Before the negative velocity perturbation can decay back to continuum levels, there is a dramatic positive velocity shift within a minute or two with an associated brightening. The typical velocity perturbation in all SCB Doppler velocity measurements is between -2 and -5 km s^{-1}.

The differences found between SCB and flare kernels are listed in tabular form in the Appendix. This table highlights how an intensity change in the Hα line center can result from distinctly different physical causes. The interpretations we draw from this difference is described below.

Conclusions

Tracking flare kernels through the evolution of the erupting flare confirms that the total sum of all the loops leads to the total intensity of the flare. Although it is not possible to say that any given kernel is tracking one specific flare loop, the flare kernels to dissect the flare into its smallest visibly resolvable components in the ISOON Hα dataset. The number of detectable kernels declines as the flare's intensity decays from its peak implying fewer resolvable components in the flare ribbons. Thus the overall intensity of the flare is decided by an exponential decay of the number of foot points visible at any given time.

Maurya & Ambastha (2010) tracked subsections of the October 28, 2003 X17 flare as it evolved. They reported peak speeds ranging from □10 – 60 km s^{-1}, depending on the part of the flare over the span of 13 minutes. Maurya & Ambastha (2010) also reported distances traveled of □10^4 km. The October 28th flare is several orders of magnitude greater in intensity than the flares considered for this study. Despite this difference, peak speeds of flare kernels are measured at □18 km s^{-1} and the mean velocity of all flare kernels is □3 km s^{-1}. The maximum distance flare kernels traveled is □2×10^4 km and the average distance traveled is □5×10^3 km. This similarity in velocity as well as distance traveled between two events of radically different intensities implies that the velocities and distances observed do not scale directly with the strength of the eruption.

SCBs are caused by hot plasma streaming along magnetic loop lines originating in the associated flare ribbons an impacting the chromosphere causing brightening to occur. This assumes the magnetic fields to be in a simple potential magnetic field configuration. This model implies that the longer the magnetic loop, the further the heated plasma has to travel and the dimmer the SCBs. The time it takes to observe a brightening is directly proportional to the lengths of the overarching loops:

$$\tau = \gamma \frac{L}{v_e}$$

where τ is the time it takes for an observed brightening to travel from the flare ribbon along the magnetic loop lines and impact the chromosphere, L is the loop length, v_e is the electron velocity along the loop line, and γ is a multiplicative factor to account for the changing plasma β parameter between the chromosphere and corona. In the idealized case, the travel time would be the Alfvén time, $\tau = \tau_A$. The Alfvén travel time is defined as:

$$\tau_A = \frac{L}{v_A}$$

where L again is the loop length and v_A is the Alfvén velocity (Aschwanden 2005). In reality, v_e is most likely some linear combination of v_A and the electron thermal velocity, v_{Te}.

The slopes determined from time-distance measurements give an approximate two different propagation speed for SCBs: □45 km s^{-1} and □142 km s^{-1} assuming the magnetic fields are a in a simple potential field configuration. The sound speed in the chromosphere is approximately c_s □10 km s^{-1} (Nagashima et al. 2009), while the Alfvén speed in the upper chromosphere is approximated to be between v_A □10 – 100 km s^{-1} (Aschwanden 2005). Both of the SCB propagation speeds are above the approximated sound speed. Both propagation speeds fall reasonably well into the range of the Alfvén speed. The different propagation speeds would then imply different layers of loops being heated as the flare erupts.

The Doppler type 3 class of SCB, present an interesting anomaly to both the other observed SCBs and the formation of a model. One explanation for the sudden positive velocity shift toward the observer is chromospheric ablation. Dennis & Schwartz (1989) proposed a physical model for particle beams impacting the upper chromosphere and thermally exciting chromopsheric material to rise up into the corona. The brightening would be visible in EUV and x-ray observations, which, if observed, would confirm this postulation.

Automated methods to track and analyze flare ribbons across multiple sources of data have been developed over the last decade with reasonable success (Qu et al. 2003; Maurya & Ambastha 2010; Gill et al. 2010). The method and results presented here suggest that flares are made up from a sum of their parts, and SCBs are different from flare ribbons and propagate at speeds near the sound speed and Alfvén speed. Doppler velocity measurements confirm the intensity measurements that at least three distinct classes of SCBs exist. Corresponding coronal measurements are needed in order to confirm the proposed topology of the overarching loop structure. With sufficient resolution and cadence of coronal images it will be possible to track the heated plasma from its origin in the flare ribbon through the corona.

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Appendix

Flare Kernels	**SCB Kernels**
Impulsive brightening	Impulsive brightening
Exponential decay	Impulsive decay
Average lifetime: 70 min	Average lifetime: 12 min
Directed motion	Random motion
Max: ~10 times background intensity	Max: ~1.5 times background intensity
Intensity coincident with flare peak	Intensity peak before flare peak
Independent of CME	Correlated with CME
Broad Doppler velocity	Impulsive Doppler velocity
Consistent appearance	Three distinct types
Apparent Speed: ~3 km s^{-1}	Propagation Speed: ~45 and □142 km s^{-1}

Table: Summarizing the results of the SCB and Flare tracking algorithm. The observed differences between flares and SCBs are highlighted.